



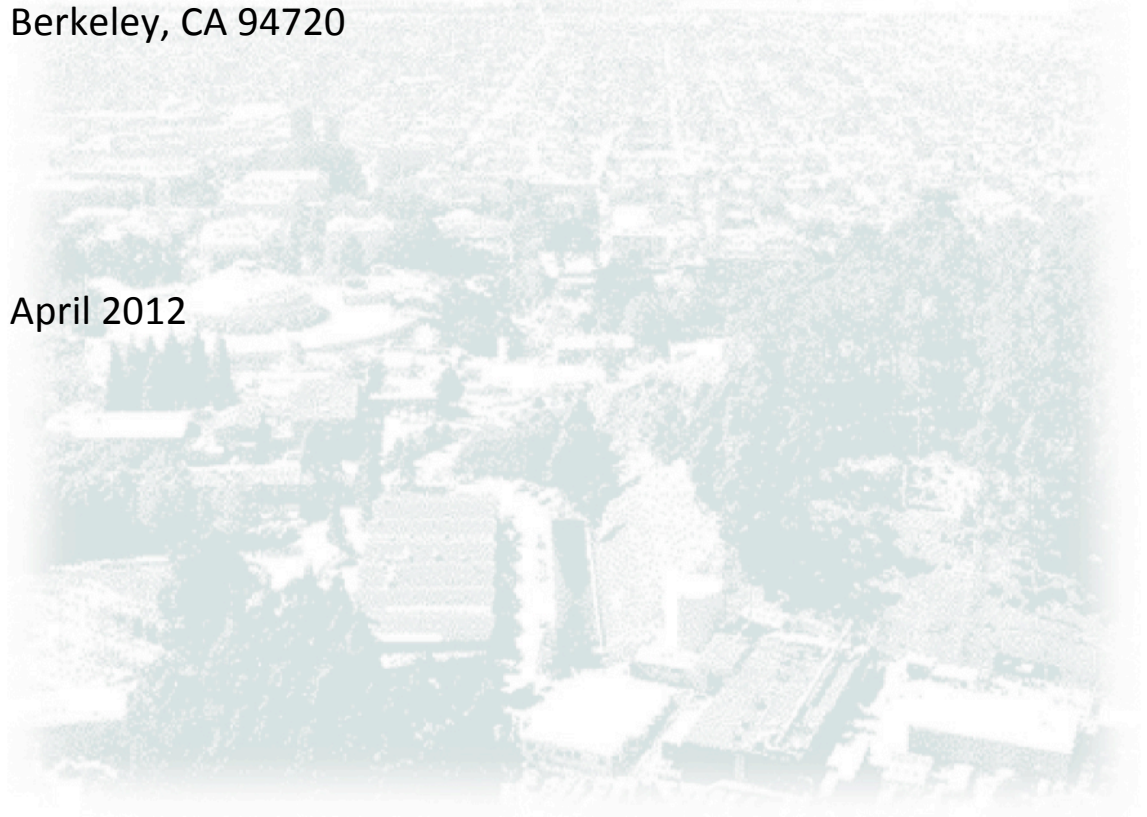
# ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

## **The Potential for Avoided Emissions from Photovoltaic Electricity in the United States**

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April 2012



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# **The Potential for Avoided Emissions from Photovoltaic Electricity in the United States**

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## **Abstract**

This study evaluates avoided emissions potential of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub>, assuming a 10% penetration level of photovoltaics (PV) in ten selected U.S. states. We estimate avoided emissions using an hourly energy system simulation model, EnergyPLAN. Avoided emissions vary significantly across the country—mainly due to three state-specific factors: the existing resource mix of power plants (power grid fuel mix), the emission intensity of existing fossil fuel power plants and the PV capacity factor within each state. The avoided emissions per solar PV capacity (g/W)—for ten U.S. states — ranged from 670–1500 for CO<sub>2</sub>, 0.01–7.80 for SO<sub>2</sub> and 0.25–2.40 for NO<sub>x</sub>. In general, avoided emissions are likely to be higher in the locations with 1) higher share of coal plants; 2) higher emission of existing fossil fuel plants; and 3) higher PV capacity factor. To further illustrate the quantitative relation between avoided emissions and the three variation factors, we conducted a sensitivity analysis. Finally, we estimated the change in avoided emissions in a coal-intensive state by varying the operational constraints of fossil-fuel power plants. At the 10% penetration level avoided emissions were not constrained by the ramp rate limitations, but the minimum capacity requirement was significantly affected the avoided emission estimates.

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Keywords: Photovoltaics; Emissions; Energy model; United States

## 1. Introduction

Renewable energy sources will play an increasing role in a future where reducing our dependence on fossil fuels and addressing environmental challenges are a priority. In the United States, Renewable Portfolio Standards (RPS), which mandate renewable energy adoption targets, have been established in nearly three-quarters of all states [1]. An RPS requires that a minimum amount of renewable energy (such as wind, solar, biomass, or geothermal energy) be included in the portfolios of electric utilities-generating resources [2]. Solar photovoltaics (PV) are a common type of renewable electricity source that reduces the demand for fossil fuels and associated emissions including CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub>. The U.S. Department of Energy (DOE) recently launched the SunShot Initiative with the goal of driving down the cost of solar electricity to \$0.06/kWh by 2030. DOE projects that reducing solar electricity costs will enable solar energy to account for 15%-18% of America's electricity generation by 2030 [3]. While deploying a larger share of solar electricity into the power grid will generally reduce fossil fuel use and associated GHG emissions and pollution, uncertainty about the magnitude of avoided fuel-use and emissions remains. Given the intermittency of PV electricity output and state-by-state differences in the mix of existing power plants, there is interest in conducting analysis to evaluate the possible range of avoided fuel use and emissions, especially when the penetration level of PV is expected to be significant (i.e., at least 10%). As an example of variation across states, coal-fired power plants account for 36% and 96% of electricity generated in Texas and West Virginia, respectively. Installing same nameplate capacity of PV in these two states will have substantially different avoided emissions, mainly because of three state-specific factors: 1) the fuel mix used to supply existing power plants, 2) the emission intensity of existing fossil fuel power plants and 3) the capacity factor<sup>1</sup> of the PV system within each state. State and regional planners tend to focus their attention on locations which have relatively abundant solar resources (i.e., places with higher PV capacity factors). However, after considering avoided emissions, the most favorable states might not necessarily be the ones with the highest solar potential. The analysis of avoided emissions may indicate significant environmental benefits not captured by analysis of solar generation potential alone. Two additional state-specific factors also need to be taken into account. Currently, federal support for solar deployment consists of tax incentives based on installed PV capacity, but does not reward solar installations that lead to reductions of pollutant emissions. An important question addressed in this paper is whether geographically targeted support for solar installations could be justified as a means for reducing regional pollutant emissions.

Here we used the EnergyPLAN modeling system to simulate PV deployment at 10% of generation for ten selected states (West Virginia, Indiana, Kentucky, Ohio, Colorado,

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<sup>1</sup> Capacity factor is defined as hourly generation (Watt) divided by system capacity (Watt). To calculate it, the following equation is also used. PV capacity factor = solar irradiation \* system ratio/(365\*24), for solar radiation and system, refer to [4] PVWATT1.0 online calculation tool, for more information from <http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/>.

Pennsylvania, Illinois, Texas, New York, and California). We selected these states, because they have a diverse mix of power plant fuels, existing emission intensity, and PV capacity factors and thereby allow for assessment of how the relative influence and importance of each state-specific factor might vary geographically.

EnergyPLAN has been used in a number of research projects related to renewable energy deployment and has been formally documented in a variety of peer-reviewed journals [5-7]. In Section 2, we discuss how other researchers have estimated avoided emissions in the United States and how EnergyPLAN has been used in related work. Section 3 introduces our modeling method and data sources. Section 4 provides background on the three state-specific variation factors among the ten selected states. Section 5 shows the results of avoided emissions of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> assuming a 10% penetration level of PV. We also discuss results of an analysis of the relationship between avoided emissions and the three state-specific factors. Section 6 introduces other factors that can influence (offset) avoided emission amounts, including power plant operational constraints. In Section 7, we summarize the limitations of this preliminary study and conclude with a discussion of future research.

## **2. Background on estimating avoided emissions and EnergyPLAN**

While many studies relate increased renewable penetration to changes in pollutant emissions, they are often focused on the marginal changes associated with an individual new installation. Over ten years ago, the U.S. Environmental Protection Agency (EPA) released a study that measured the emission reductions after 29 PV systems were installed on residential and commercial building rooftops across the U.S. [8]. This author used PV output and utility emissions data from EPA's Acid Rain Program to evaluate simulation results from the PVWATT model [9]. Other studies [10-12] have estimated emissions from natural gas-fired generators used to provide grid support for variable renewable power sources including wind. Avoided CO<sub>2</sub> emissions at different fuel mix scales in the U.S.—assuming varied PV penetration levels—have also been modeled [13]. The avoided emissions these papers [8-13] reported were limited to individual PV installation sites and the avoided fuel use came from an individual (marginal) power plant that would have supplied that energy in the absence of the PV capacity.

To better understand the benefits and impacts of increased deployment of PV systems, the environmental benefits from not only individual PV plants, but also high percentage of PV penetration, should be analyzed. In a more recent study of future PV growth, U.S. researchers introduced a simple linear model that estimated mid-century avoided greenhouse gas (GHG) emissions across the country [14]. However, the linearity of the model limits accuracy of the study. Another relevant study [15] used a unit commitment (i.e., dispatch) model to explore the relationship between detailed plant operational characteristics and changes in emissions levels for generators in the power grid of California and Colorado. However, dispatch models are very complicated and are built on detailed information for individual power plants and transmission lines. For this reason, it is not easy to use these types of modeling tools for a relatively larger

area, and thereby assess sensitivities and differences in findings across more diverse geographies. Study [16] conducted a detailed review and compared the advantages and disadvantages of different models—within the context of estimating avoided emissions from increased renewable penetration.

For the question we are targeting in this study (what is the potential for avoided emissions from high penetration of PV in the U.S.) and considering of both accuracy and scale of the models, a review of previous literature indicates that there are no existing studies that have given a robust answer. To answer this question in this study, the first step entailed selecting a suitable energy modeling system based on a number of important criteria. Our choice of an energy modeling system had to be able to evaluate results at the hourly level given the highly variable output of PV electricity generation. Second, the model should be able to handle significant changes to the assumed mix of power plant fuels—since we are evaluating high PV penetration scenarios. Finally, the ideal modeling system should be able to evaluate results across a relatively large spatial scale (state, regions, or at the national level). For these reasons, we selected the EnergyPLAN modeling system to evaluate future electricity generation and avoided emissions in the United States assuming higher PV electricity penetration [17, 18]. A detailed review of modeling tools for the energy sector was discussed in [19]. The EnergyPLAN model has been used in many international studies related to renewable energy integration. For example, wind power penetration in the Danish [7], Irish [6], Italian [5] and Chinese [20] energy systems has been evaluated using EnergyPLAN.

### 3. Modeling method and data

The EnergyPLAN model solves an optimization problem that balances electricity system demand and supply (see [17] page 64) while minimizing fossil fuel use (coal, natural gas or oil) in order to meet an hourly demand profile. Equation (1) describes the general optimization function used in the EnergyPLAN modeling system.

Minimize  $\{F\}$

Subject to the constraint:  $E_i = D_i \quad i=1, 2, \dots, 8784$  (1)

Where: F denotes fossil fuel use; E denotes electricity generation; D denotes demand, i denotes hour in one year.

The order of displacing fuel is based on capacity factors (lower capacity factors mean a power plant produces generation less frequently over the course of a year). The model solves so that lower capacity factor natural gas/oil-fired power plants are displaced first followed by coal. Coal plants have the highest capacity factor among fossil fuel power plants, and are therefore displaced last.

The validity of simulated results from EnergyPLAN were tested under different conditions by previous authors [5, 6, 20]. For example, EnergyPLAN's simulated results were accurate to within 0.47% when compared to actual power plant production data in the Irish energy system [6]. The analysis of this study is based on the assumption that EnergyPLAN is capable of providing accurate simulation results when compared to real data in the United States.

In this analysis, we specified the following inputs for EnergyPLAN: (1) hourly demand; (2) capacity from multiple types of power plants including coal, natural gas, oil, nuclear, hydroelectric, wind, solar, geothermal, and (3) hourly generation from solar and wind plants. Given these inputs, the EnergyPLAN model produces output including hourly generation (MWh) from coal, natural gas and oil-fired power plants assuming 10% of electricity was generated from PV systems. We use the hourly results to calculate the total avoided emission of power plants for one year (2009 is the base year in this analysis).

For our initial analysis, we assumed that there was no electricity imported and/or exported between the states (i.e., each state is evaluated within a closed system). Obviously, in the real world, electricity imports and exports occur between states on a very frequent basis. Section 6.2 will discuss this assumption in greater detail. We incorporated hourly demand data from five key sources: (1) Ventyx Velocity Suite by ABB which is a widely-used database for electricity market analysis [21]; (2) annual generation data from U.S. Department of Energy's Energy Information Administration (EIA) [22]; (3) wind data from the California and Texas grid operator (CAISO and ERCOT) [23, 24], because they are the states which have non-trivial wind installation and have report hourly wind generation data; (4) solar data from National Renewable Energy Laboratory's System Advisor Model (SAM) [25]; and (5) emissions data from the U.S. Environmental Protection Agency's (EPA) eGRID database [26]. The emissions and hourly generation data allowed us to calculate state-by-state avoided emissions. Table 1 summarizes the key inputs, outputs, temporal scale, and sources of data for our initial analysis.

**Table 1: Input data sources, temporal scales, outputs, and units**

Category	Data description	Temporal scale and units	Data sources
Key EnergyPLAN Inputs	Electricity demand	Hourly MW	Ventyx [21]
	Generation and capacity from power plants (excluding wind and solar)	Annual MWh	EIA [22]
	Generation from wind power sources	Hourly MW	CAISO [23]; ERCOT [24]
	Generation from PV power sources	Hourly MW	SAM [25]
EnergyPLAN Output	Generation from power plants after PV penetration	Hourly MW	Results of this study
Other Analysis Input(s)	Average emission for CO <sub>2</sub> , SO <sub>2</sub> , and NO <sub>x</sub>	tonnes/MWh	eGRID [26]
Key Analysis	Avoided emissions assuming 10%	tonnes	Results of this

Output	PV penetration levels		study
	Avoided emissions assuming 10% PV penetration levels	g/W	Results of this study

#### 4. State-specific variation

As discussed earlier, there are three state-specific factors that affect the estimation of avoided emissions within a particular state: 1) the fuel mix used to supply existing power plants, 2) the emission intensity of existing fossil fuel power plants and 3) the capacity factor of the PV system within each state. For example, coal-fired power plants in California provide less than 1% of electricity, but they provide nearly all power generated within West Virginia. It follows that a higher penetration of PV in West Virginia will lead to a larger relative reduction in emissions per kWh of production when compared to states with a cleaner portfolio of existing generation, assuming local coal generation is displaced and not simply transferred elsewhere.

Twenty five years ago, Calzonetti et al.[27] noted that decisions about power plant locations and fuel types are based on environmental regulations, the price of fuels, electric utility policy, fuel availability, electricity demand, interrelationships with neighboring power systems, and other factors. Pacific Coast states—including California—generate the majority of their electricity using natural gas and hydroelectric resources. In contrast, the U.S. Midwest and some Eastern states including West Virginia, Indiana, Kentucky, Pennsylvania, and Ohio typically generate the majority of their electricity using coal. Higher levels of PV (or other renewable) penetration could displace energy provided from different types of power plants depending on the location of the new capacity. For example, increased electricity generated from PV in West Virginia could displace a larger share of coal-fired generation when compared to California where PV could displace a larger share of natural gas. However, the actual energy produced from renewable resources—and any avoided emissions from displaced fossil units—are also affected by local weather conditions that vary from state-to-state. For this study, we selected 10 states across the U.S. that are geographically distributed and typically generate the majority of their electricity from coal or natural gas. Table 2 shows that the share of fuel used to generate electricity for the ten states in our analysis.

**Table 2: Power grid fuel mix for ten selected states in 2009 (Source: [22])**

State	Net generation (GWh)	Generation resource mix (percent share)			
		Coal	Natural Gas	Nuclear	Other
West Virginia	70,780	96.2	0.4	0	3.4
Indiana	116,670	92.8	3.4	0	3.7
Kentucky	90,630	92.7	3.2	0	4.1
Ohio	139,090	81.8	4.3	10.9	3.0
Colorado	50,570	62.6	27.4	0	10.0
Pennsylvania	219,500	48.1	13.7	35.2	3.0
Illinois	193,860	46.4	2.4	49.2	2.0
Texas	397,170	35.0	48.0	10.4	6.6
New York	133,150	9.6	33.4	32.7	24.4



California	204,780	1.0	56.2	15.5	27.3
US	3,950,330	44.4	23.3	20.2	12.0

Table 3 shows that the emission intensity from existing fossil fuel power plants vary considerably across the ten states. For example, the SO<sub>2</sub> emissions from coal plants range from 1.87 (g/kWh) in Colorado to 8.22 (g/kWh) in Pennsylvania.

**Table 3: Emission of fossil fuel power plants for ten selected states (Source: [26])**

State	CO <sub>2</sub> (g/kWh)		SO <sub>2</sub> (g/kWh)	NO <sub>x</sub> (g/kWh)
	Coal plants	Natural Gas plants	Coal plants	Coal plants
West Virginia	1005	690	4.43	1.70
Indiana	1067	519	5.85	1.61
Kentucky	1080	703	4.03	1.85
Ohio	1029	546	7.17	1.80
Colorado	1139	511	1.87	1.80
Pennsylvania	1005	479	8.22	1.51
Illinois	1125	520	3.03	1.25
Texas	1141	469	3.34	0.84
New York	1046	532	4.38	1.18
California	822	456	4.37	3.47
U.S.	1077	482	4.49	1.58

The state-specific variation of solar irradiation is the primary determinant of the capacity factor of a PV system, assuming identical PV technologies and operational practices. We used the National Renewable Energy Laboratory's System Advisor Model (SAM) to generate hourly PV electricity output within the ten states of our analysis. Table 4 shows the SAM-generated assumptions of capacity factors for PV systems installed in the ten locations evaluated in this study (assuming a 10% energy penetration level).

**Table 4: PV capacity with 10% PV installation for ten selected states (data generated using System Advisor Model [25])**

State	PV generation (GWh)	Installation location	Capacity factor	PV capacity (MW)
West Virginia	7,080	Charleston	0.158	5110
Indiana	11,670	Indianapolis	0.173	7,700
Kentucky	9,060	Louisville	0.175	5,910
Ohio	13,910	Columbus	0.158	10,050
Colorado	5,060	Colorado Springs	0.226	2,550

Pennsylvania	21,950	Philadelphia	0.172	14,570
Illinois	19,390	Chicago	0.168	13,170
Texas	39,720	El Paso	0.245	18,510
New York	13,320	Rochester	0.156	9,740
California	20,480	Daggett	0.261	8,960
U.S.	395,030	Assuming in Colorado Springs, CO <sup>2</sup>	0.226	199,540

## 5. Results

We report results including the total amount of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> emissions attributable to existing plants in 2009 along with the estimated percentage of emissions reduced for each state from our hypothetical 10% increase in PV penetration. To make the benefits from PV comparable across states, we present avoided emissions expressed in g/W of PV installed capacity. We also conducted a sensitivity analysis to investigate the relationship between the spatial variation factors and the avoided emissions.

### 5.1 Avoided emissions potential

Table 5 shows the baseline emissions of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> for each state and the estimated avoided emissions—expressed as a percentage reduction—after 10% PV penetration. As expected, the percentage of avoided emissions varies significantly across the ten states. For example, the avoided SO<sub>2</sub> emission for West Virginia is 10.2%, while Texas is only 0.1%. This difference is primarily caused by the higher share of coal used to generate electricity in West Virginia compared to Texas.

**Table 5: Total amount of avoided emissions of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> for ten selected states**

	CO <sub>2</sub> (Mton)		SO <sub>2</sub> (kton)		NO <sub>x</sub> (kton)	
	original	% avoided	original	% avoided	original	% avoided
West Virginia	69	10.3	302	10.2	116	10.3
Indiana	118	8.3	634	7.6	175	7.7
Kentucky	93	9.7	339	8.9	157	9.1
Ohio	123	10.3	833	9.4	210	9.6
Colorado	43	7.4	59	1.9	61	3.8
Pennsylvania	121	12.1	867	8.6	162	9.1
Illinois	104	18.8	274	18.2	114	18.5
Texas	248	6.5	465	0.1	158	4.7
New York	37	17.6	62	6.5	27	13.5
California	54	15.5	10	1.1	21	10.6

<sup>2</sup> This location has higher solar resource than average level in the U.S.

U.S.	2339	8.5	7960	3.6	3013	5.5
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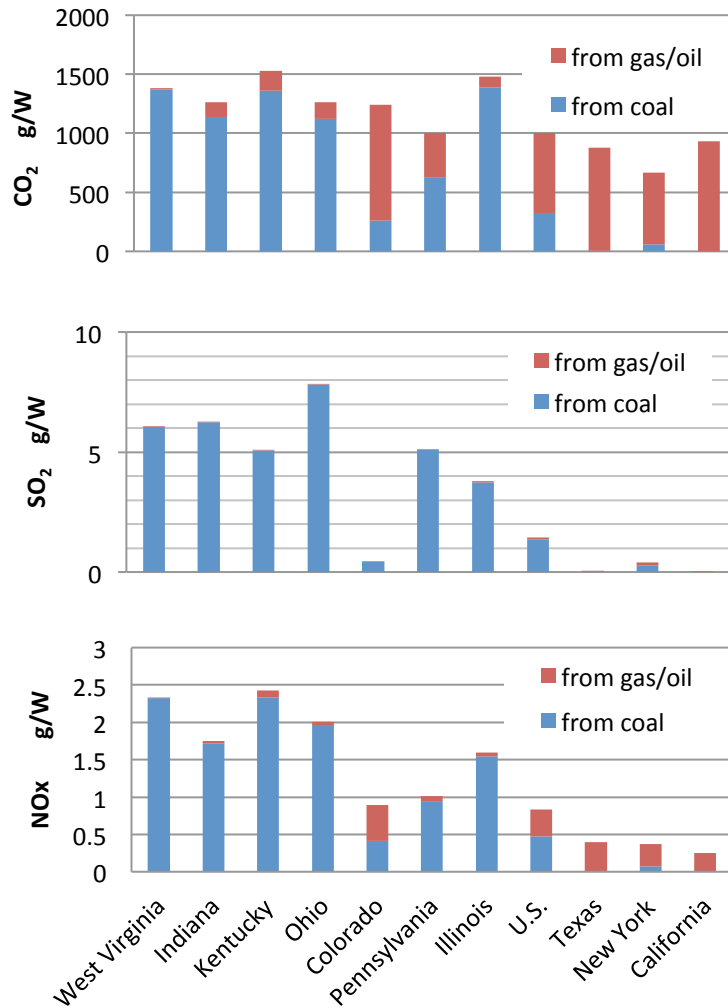
## 5.2 Avoided emissions potential in g/W

To compare the effect of increased PV installation across states, we present the avoided emission potential in units of avoided g/W, which is the total avoided emissions divided by statewide PV installed capacity. Table 6 shows the results from this comparative analysis. The avoided emission per solar PV capacity (g/W)—for ten U.S. states — ranged from 669 (New York) to 1480 (West Virginia) for CO<sub>2</sub>, 0.01 (California) to 7.82 (Ohio) for SO<sub>2</sub> and 0.25 (California) to 2.42 (Kentucky) for NO<sub>x</sub>.

**Table 6: Avoided emission potential of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> for ten selected states**

State	Avoided emissions (g/W)		
	CO <sub>2</sub>	SO <sub>2</sub>	NO <sub>x</sub>
West Virginia	1384	6.04	2.33
Indiana	1262	6.24	1.75
Kentucky	1526	5.08	2.42
Ohio	1261	7.82	2.00
Colorado	1241	0.43	0.90
Pennsylvania	1003	5.11	1.01
Illinois	1480	3.78	1.60
Texas	876	0.02	0.40
New York	669	0.41	0.37
California	934	0.01	0.25
U.S.	1000	1.45	0.83

Figure 1 shows the avoided emission potential after increased PV penetration levels by type of fuel displacement (either coal or natural gas/oil) estimated by the EnergyPLAN model.

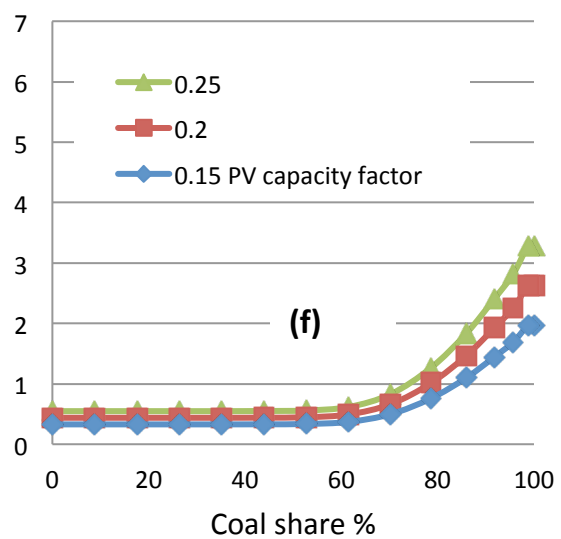
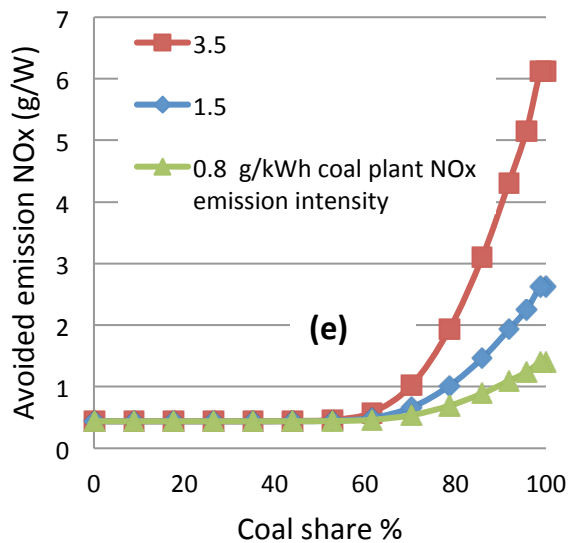
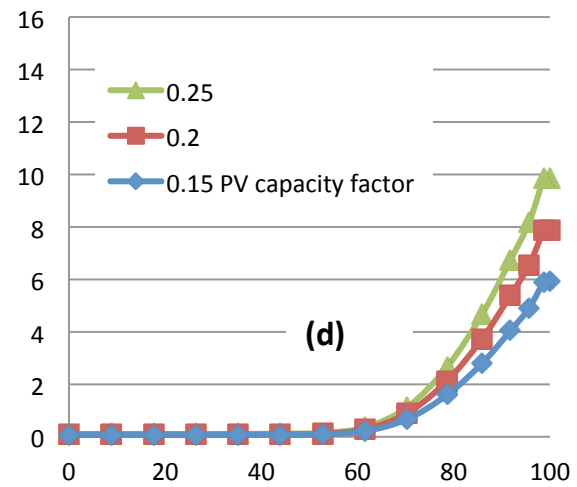
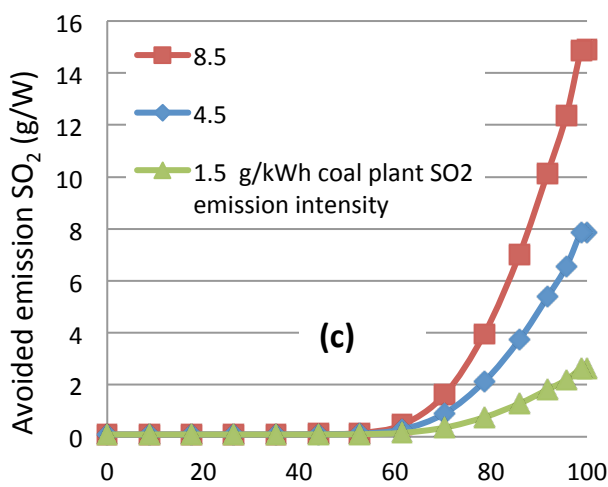
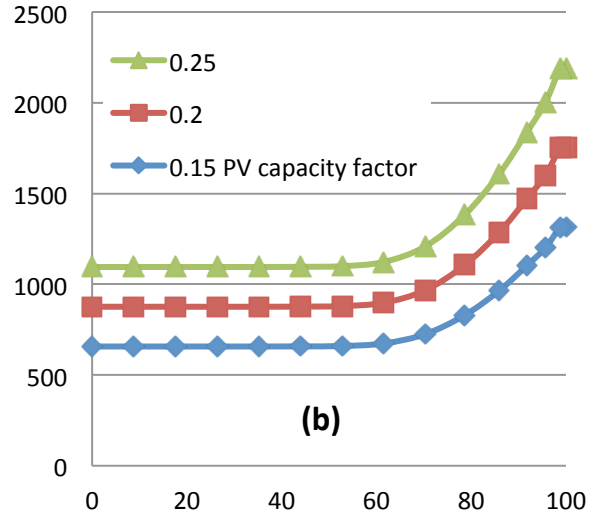
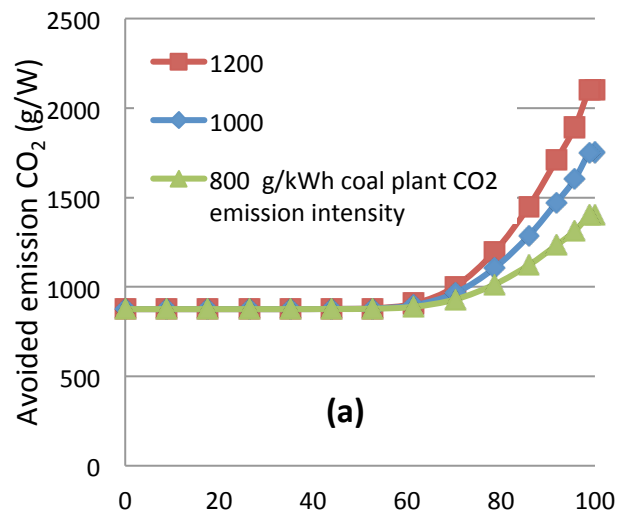


**Figure 1: Avoided emission after 10% PV penetration by type of fuel displacement (coal or natural gas/oil): (a) CO<sub>2</sub>; (b) SO<sub>2</sub>; (c) NO<sub>x</sub>**

### 5.3 Sensitivity analysis of avoided emissions

Table 6 and Figure 1 show that avoided emissions vary considerably by state. Before any quantitative analysis to explain such variation, it is obvious that qualitatively, avoided emissions of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> should be higher in the locations with higher share of coal plants, e.g. West Virginia, given that coal plants have higher emissions than any other types of power plants. To investigate the relationship between the avoided emission in g/W and the state-specific factors quantitatively, a sensitivity analysis is performed. The results are presented in Figure 2. We assume a generic state profile with 100 TWh annual demand and the fuel type of generation are coal and natural gas. Then we run EnergyPLAN model with the varying factors (the share of coal or gas generation).

We have mentioned that in general, the avoided emissions are higher in the states which have higher share of coal plants (coal share). Whether it is a linear relationship or a non-linear one with some threshold point, Figure 2 tells us the answer. We found that avoided emissions remain virtually constant when coal share increase, but after a point of 60% they increase with coal share. We believe the explanation is that if coal share is below 60%, the only fossil fuel PV replaces would be natural gas/oil, no matter the coal share is 50% or 10%. But if the coal share is above 60%, PV would replace a mix of coal and natural gas/oil. Besides gas share, we also look at how various emissions intensity of existing coal plants affect the avoided emissions. Figure 2 (a), (c), (e) shows the results. The sensitivity analysis is especially necessary for  $\text{SO}_2$  and  $\text{NO}_x$ , because the results vary more considerably than  $\text{CO}_2$ . The reason is not difficult to explain if we look at Table 3 how dramatic the variation of  $\text{SO}_2$  emission intensity of existing coal plants among states is. That may draw attention to decision-makers of PV siting among states if considering of environmental benefits of reducing pollutants, that states with high coal but low solar capacity should still be considered due to the potential for high avoided emissions. The third variation factor affecting the avoided emission rate is the PV capacity factor. Figure 2(b), (d), (f) show how the avoided emission rate changes with various PV capacity factors. The range of PV capacity factor is from 0.15 to 0.25, which almost covers the PV capacity factor across the nation.



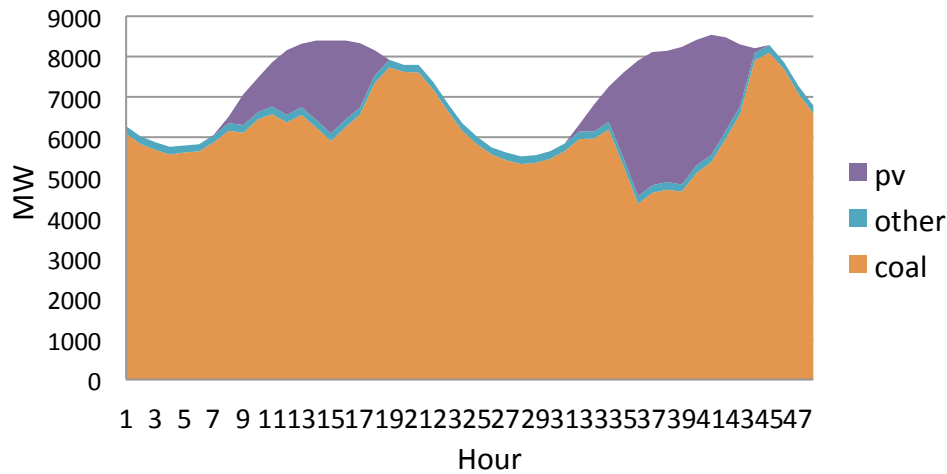
**Figure 2: Avoided emission in g/W -- (a), (c), (e) various coal share and coal plant emission intensity; (b), (d), (f) various coal share and PV capacity factor**

## **6. Operational constraints of fossil power plants from a technical perspective**

The results we have obtained from previous sections are based on the assumption that the power grid itself is flexible and reliable enough to digest all electricity coming from PV. However, there are many constraints that limit higher penetration levels (e.g. 10% and above) for intermittent renewable resources, including PV. Such constraints could offset the environmental benefits (decrease the amount of avoided emissions) caused by PV deployment. This study limits the scope of the discussion to operational constraints (for a discussion of economic constraints, please refer to [28]) from conventional fossil fuel generation [29] including ramp rate and minimum operational capacity. It should be mentioned that operational/technical constraints are not limited to these two. Other operational constraints that are not evaluated here include stability issues related to voltage and frequency, harmonics, and islanding problems. For a detailed review of these operational challenges as well as a discussion of potential solutions, the reader is referred to [30]. It was noted that these stability problems could be partly solved by optimizing design of inverter, which connects PV into power grid. However, some issues such as slow transients due to clouds are relatively difficult to solve when the penetration level of PV is high [31]. We found very little other research that discusses a maximum penetration level, but it is clear that this level depends on the geographic distribution of the PV systems [32]. For example, one study concluded that for a centrally located PV plant, the highest penetration level is 5% [33]; while another study estimated that penetration levels in a distributed PV system could reach 15% [34].

### **6.1 Ramp rate of fossil fuel power plants**

This section discusses whether coal plants or natural gas plants ramp rates constrain PV penetration and thus reduce the avoided emissions potential we estimated in previous sections. We found that PV output will probably not be constrained by fossil fuel-fired power plants ramp rates. By running EnergyPLAN model for the case study of West Virginia, Figure 3 shows West Virginia's hourly generation during two typical summer days—assuming a 10% PV penetration level. As the sun sets (i.e., 17:00-21:00), PV output drops quickly. During this time, coal plants need to quickly ramp up their generation levels to meet the demand that is no longer being met by PV. In this example, the required maximum ramp rate is estimated at 13% of capacity per hour (occurring at hour 19:00 of the second day).

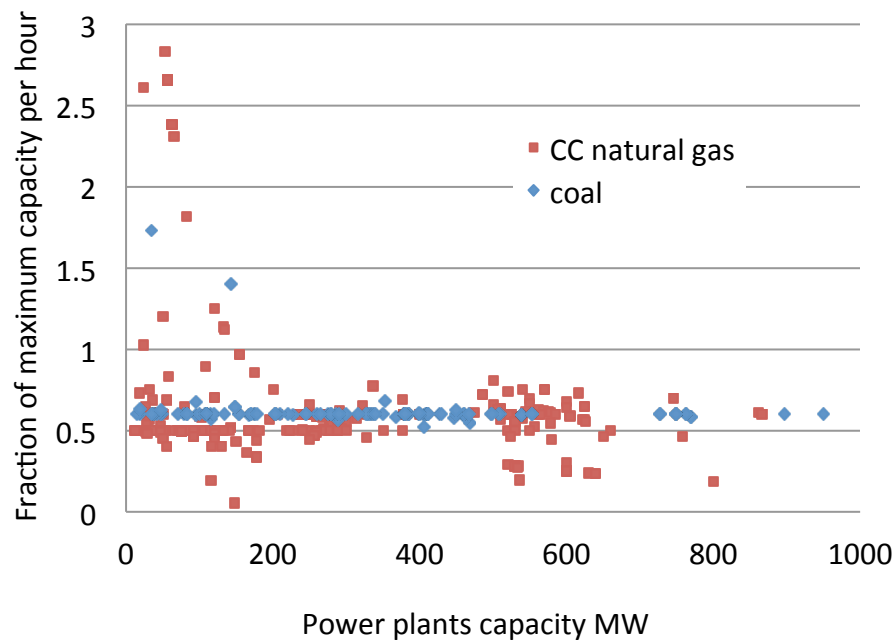


**Figure 3: Hourly generation of two typical summer days in West Virginia assuming 10% PV penetration**

To answer the question of whether fossil fuel plants ramp rate could meet this 13% requirement, we conducted an examination of the effect of ramp rates for two types of power plants (coal plants and combined cycle natural gas). These two types of base-load fossil-fired power plants have relatively slower ramp rates, so these operational constraints might affect future PV penetration. In a study of [35], the Western Electricity Coordinating Council (WECC) assumed that ramp rates for most coal plants are approximately 60% of maximum capacity per hour. WECC also assumed that ramp rates for most combined-cycle natural gas plants ranged from 20 to 70% of maximum capacity per hour. Figure 4 shows reported ramp rates for coal and combined cycle natural gas power plants.

WECC's ramp rate assumptions about the ability of coal (~60% per hour) and combined cycle natural gas units (20-70% per hour) are typically larger than the coincident decrease in PV production as the sun sets (13% in the West Virginia example). Obviously, extreme weather or other factors may increase demand at rates that cannot be met by fossil fuel power plants. However, in this simple case study, we concluded that ramp rate constraints are not likely to affect PV integration at the 10% penetration level for typical demand profiles





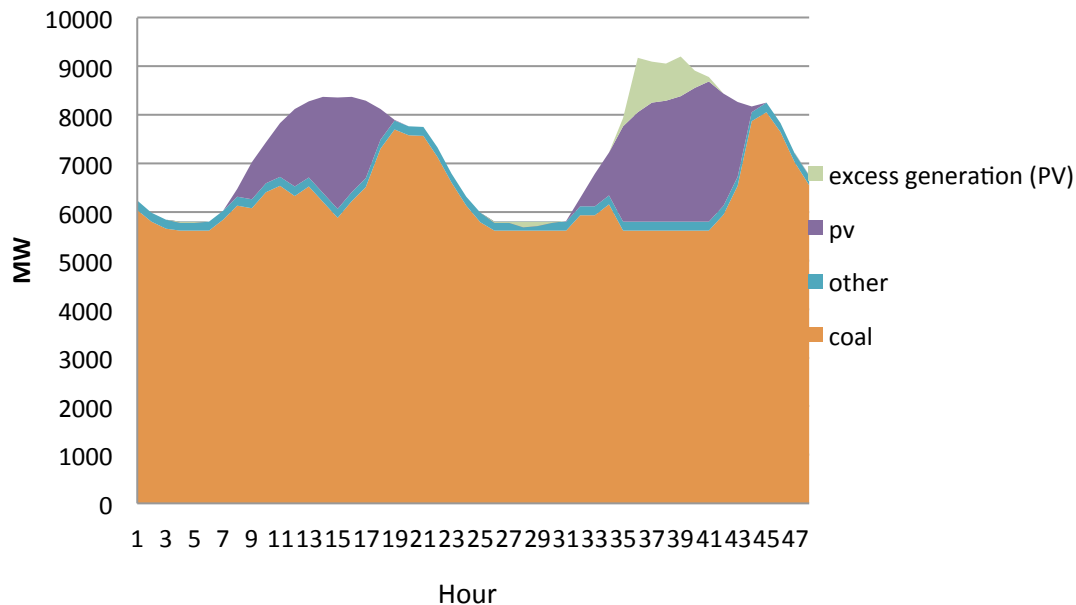
**Figure 4: Ramp rates of fossil fuel power plants**

## 6.2 Minimum capacity requirement of coal plants

We could not find evidence that ramp rates of coal and combined cycle gas plants will (generally) put constraints on future PV penetration. However, we did find that minimum capacity requirements for coal plants do affect the potential for PV penetration and could offset any associated environmental benefits from avoided emissions. In the case study of 10% PV penetration in West Virginia, operational capacity of coal plants are predicted in the modeling run to drop below full capacity at times throughout the day (see Figure 5). However, to maintain the normal function of coal plants, there is a requirement of minimum capacity (in terms of percentage of full capacity) [5]. According to a 2003 study of wind integration into the grid, at 70% of full capacity and above, no problems were reported for coal power plants. However, coal power plants may not function appropriately at or below 30% of full capacity [36]. Accordingly, between 30% and 70% of full capacity, some plants will face technical constraints and others will not.

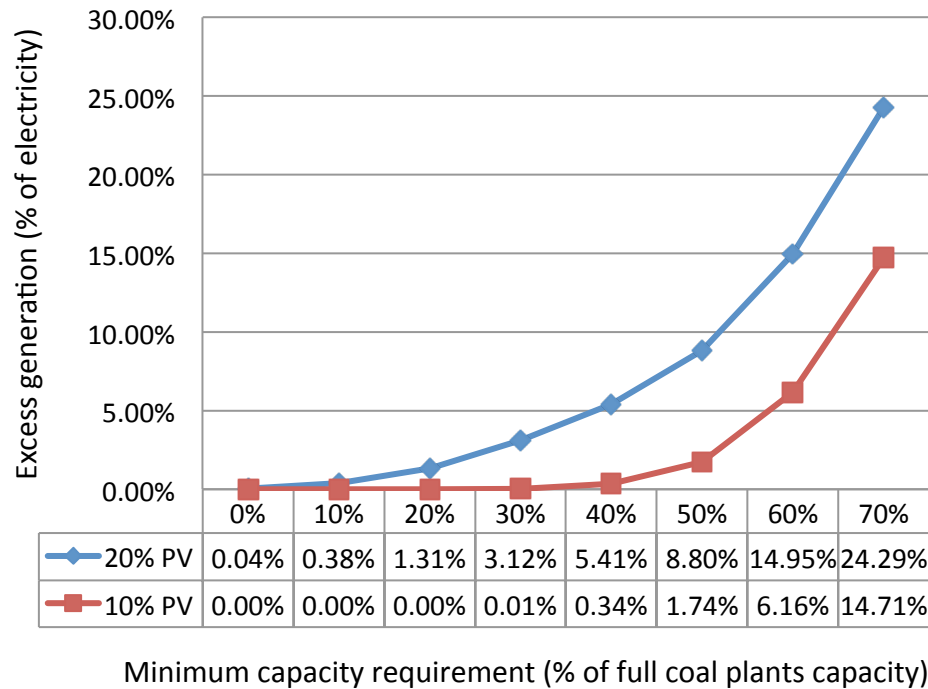
Here we ran EnergyPLAN to evaluate the effects of maintaining minimum operational capacities (50% of capacity) for coal power plants, while introducing 10% PV penetration levels into the grid. The addition of such a constraint means that some of the output from PV cannot be fed into the power grid (assuming there are no exports/imports between states). In this study, we refer to any unused PV output as “excess generation” (see Figure 5). Obviously, because states typically

import and export power, this approach can be used to understand the transmission requirements and facilitate optimization for interstate transmission of excess generation in future analyses.



**Figure 5: Hourly generation of typical summer days in West Virginia with 10% PV considering 50% of minimum capacity constraints of coal plants**

Figure 6 shows the excess generation with 10% or 20% PV penetration given the minimum capacity restraints for coal plants in West Virginia. For example, if the minimum capacity requirement is 50%, the excess generation from 10% of PV is 1.74%. Thus, the avoided emissions would be offset by 17.4% (1.74% divided by 10%) — CO<sub>2</sub> from 1384 to 1143 g/W, SO<sub>2</sub> from 6.04 to 4.99 g/W, NO<sub>x</sub> from 2.33 to 1.92 g/W. This analysis could be extended to other states to help identify the offset to the results of avoided emissions caused by excess generation.



**Figure 6: Excess generation after varying PV penetration levels and minimum capacity requirements for coal plants in West Virginia**

## 7. Conclusions and limitations

This study modeled the avoided emissions potential of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> assuming 10% PV penetration and reported the results for ten selected states in the U.S. The avoided emission (g/W) ranged from 669 to 1480 for CO<sub>2</sub>, 0.01–7.82 for SO<sub>2</sub> and 0.25–2.42 for NO<sub>x</sub>. The variation mainly due to three state-specific variation factors 1) the fuel mix used to supply existing power plants, 2) the emission of existing fossil fuel power plants and 3) the capacity factor of the PV system within each state. The results could remind policy makers when considering the location of PV deployment not only focus their attention on locations which have relatively abundant solar resources (i.e., places with higher PV capacity factors), but also states whose existing power plants are highly pollutant-intensive.. We found that in general avoided emissions of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> are higher in the locations with 1) higher share of coal plants; 2) higher emission of existing fossil fuel plants; and 3) higher PV capacity factor. To further illustrate the quantitative relation between avoided emission and the three variation factors, we conducted a sensitivity analysis. The sensitivity analysis is especially interesting for SO<sub>2</sub> and NO<sub>x</sub>, because the results vary more considerably. More attention may be paid to states which have higher emission intensity of existing plants. We also studied how the operational requirements of fossil-fired power plant could constrain the increasing levels of solar penetration. We did not find any evidence that coal and gas-fired power plant ramp rate would constrain 10% PV development. However, we did find that minimum capacity requirements for coal-fired plants may lead to excess (unused) generation of PV and offset the avoided air pollution. In such situations,

decision makers might opt for a lower PV penetration or redouble efforts to integrate with regional (out of state) grids so that the excess generation is not unused.

The sensitivity analysis could be applicable for other states to identify avoided emissions potential if the fuel mix in that state has a 40% or more fossil-fired generation. But for states have more hydro or nuclear (Washington, Vermont, etc), further research will need to be conducted. We limited our constraints analysis to two operational characteristics. In the future, a fully integrated economics-operational constraint model could be constructed to provide further insight into the issue of avoided emissions from increased PV penetration levels. The study did not consider electricity transmission between states; instead, the concept of excess generation was introduced to explore potential inefficiencies from increased PV integration into a constrained system. This study provides a preliminary framework that could be used to extrapolate results from ten selected states to other states. In addition to improving modeling methods and assumptions, future work should also investigate the air quality and regional climate impacts from the avoided emissions reported in this analysis.

### **Acknowledgments:**

This work was supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

We thank Andrew Mills, Nancy Brown, Thomas McKone, Jeffery Greenblatt and Chuck Goldman for helpful discussion and comments.

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